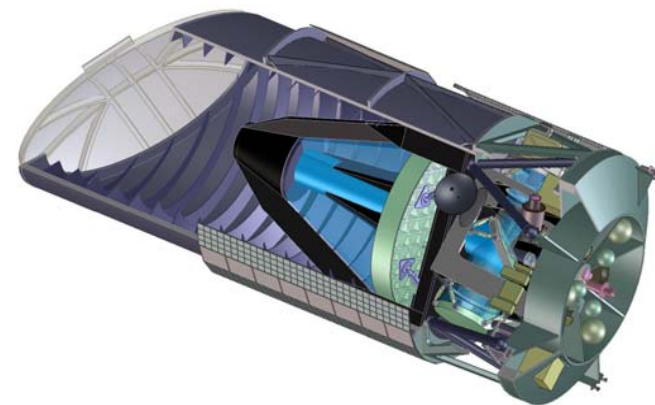
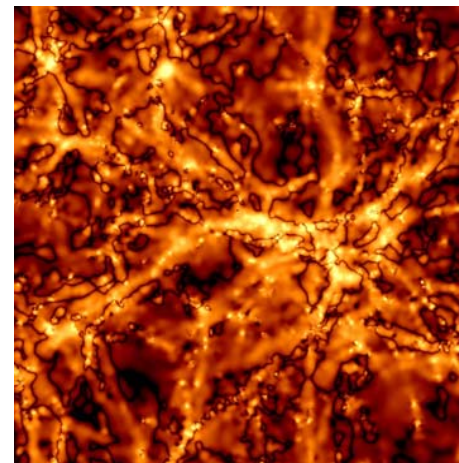


Cosmology Theory and Phenomenology at LBL



Eric Linder
11 November 2004



With every new discovery in physics, there is less of a dividing line between
Particle Physics and **Astrophysics**.

Inflation:

Particle accelerators
GUT scale physics

Early universe
Origin of matter,
gravitational waves

Dark Energy:

vacuum energy,
quantum fields,
extra dimensions

acceleration of the universe
fate of the universe

Dark Matter:

LHC, direct detection

galaxy clusters, gravit'l lensing

With every new discovery in physics, there is less of a dividing line between
Particle Physics and **Astrophysics**.

Inflation: “**Tevatron** → **Planck-otron**”

Particle accelerators
GUT scale physics

Early universe
Origin of matter,
gravitational waves

Dark Energy: “**Quantum Cosmology?**”

vacuum energy,
quantum fields,
extra dimensions

acceleration of the universe
fate of the universe

Dark Matter: “**SUSY in the sky**”

LHC, direct detection

galaxy clusters, gravit'l lensing

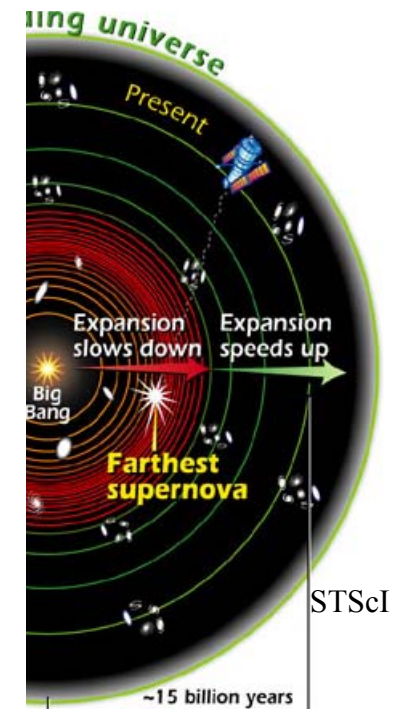
Cosmology connects

- high energy physics and gravitation
- the early universe, the present, and our fate

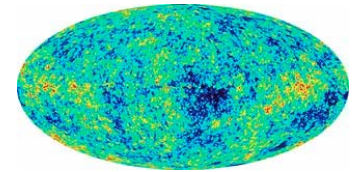
We can probe physics throughout the history of the universe, in many ways.



Supernovae (SN Ia) directly map the expansion history of the universe –
discovering acceleration contrary to gravity, arising from “dark energy”.

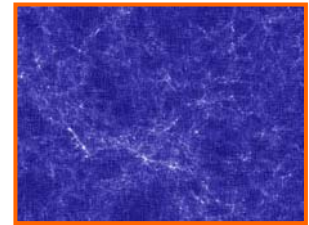


Relic imprints of quantum particle creation in the CMB from *inflation* - epoch of acceleration at 10^{-35} s and energies near the GUT scale (*trillion times higher than in particle accelerators*).



CMB

These *ripples in energy density* also occur in matter, as denser and less dense regions.



LSS

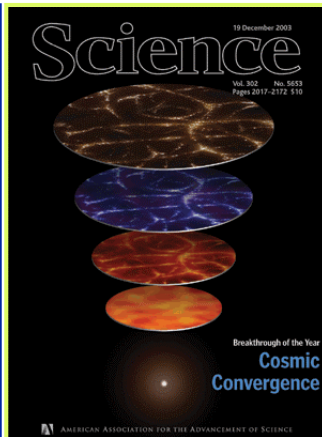
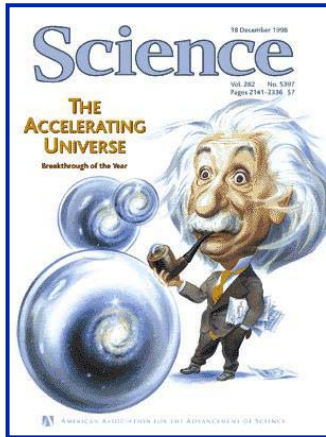
Denser regions get a “head start” and *form into galaxies and clusters* of galaxies. How quickly they grow depends on the *expansion rate* of the universe (*traced by SN*).



SN

It's all connected.

National priorities



OSTP “Physics of the Universe” report
Highest priority: Exploring the nature of dark energy
Next step: “Decisive measurements” of CMB polarization

Breakthroughs of the Year 1998, 2003

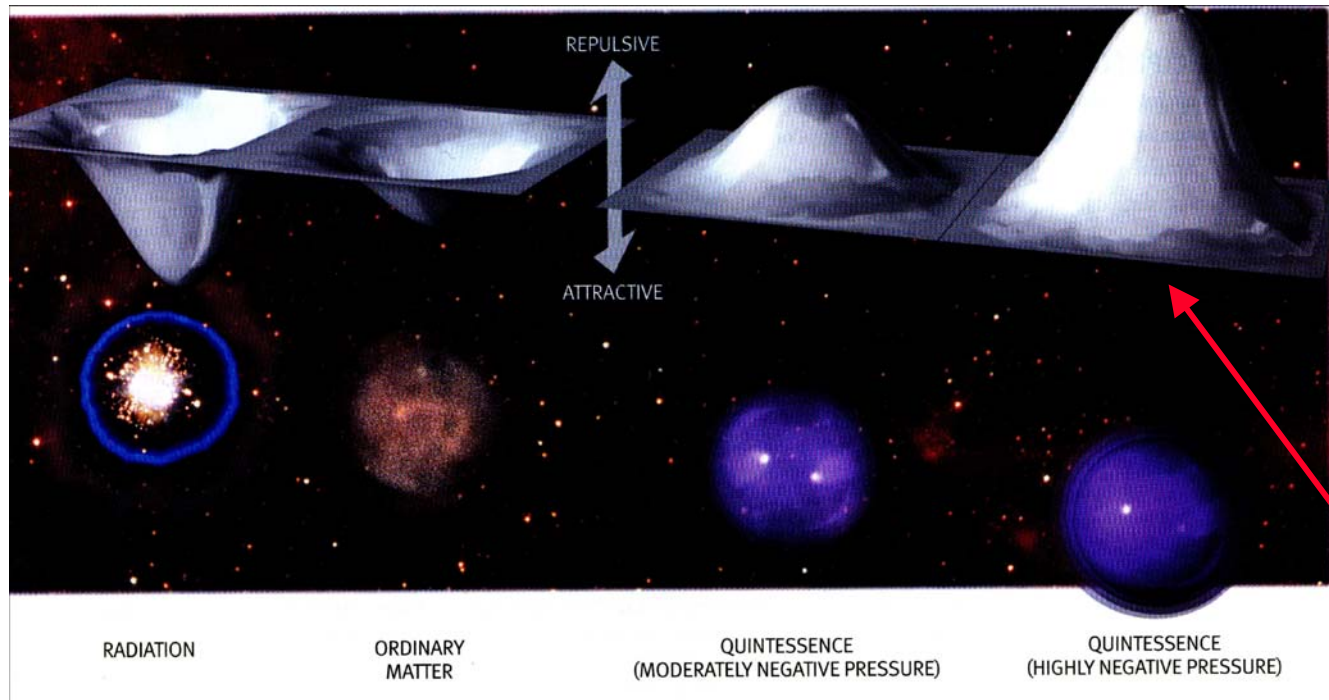


#3 - SNAP

11 Science Questions for the New Century (NRC)
“Determine the properties of dark energy”



Beyond Einstein: What happens when gravity is no longer an attractive force?



Scientific American

Discovery (SCP 1998): 70% of the universe acts this way! Fundamentally new physics.

Dark energy = quantum vacuum energy?

We need to explore further frontiers in high energy physics, gravitation, and cosmology.

New quantum physics?

Quintessence (atomic particles, light, neutrinos, dark matter, and...), **M/String theory**

New gravitational physics?

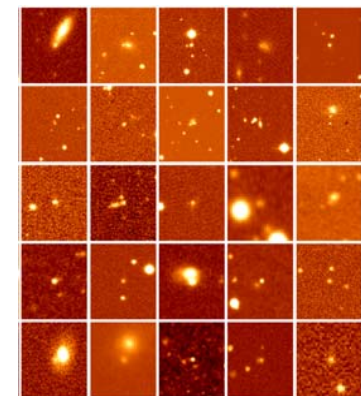
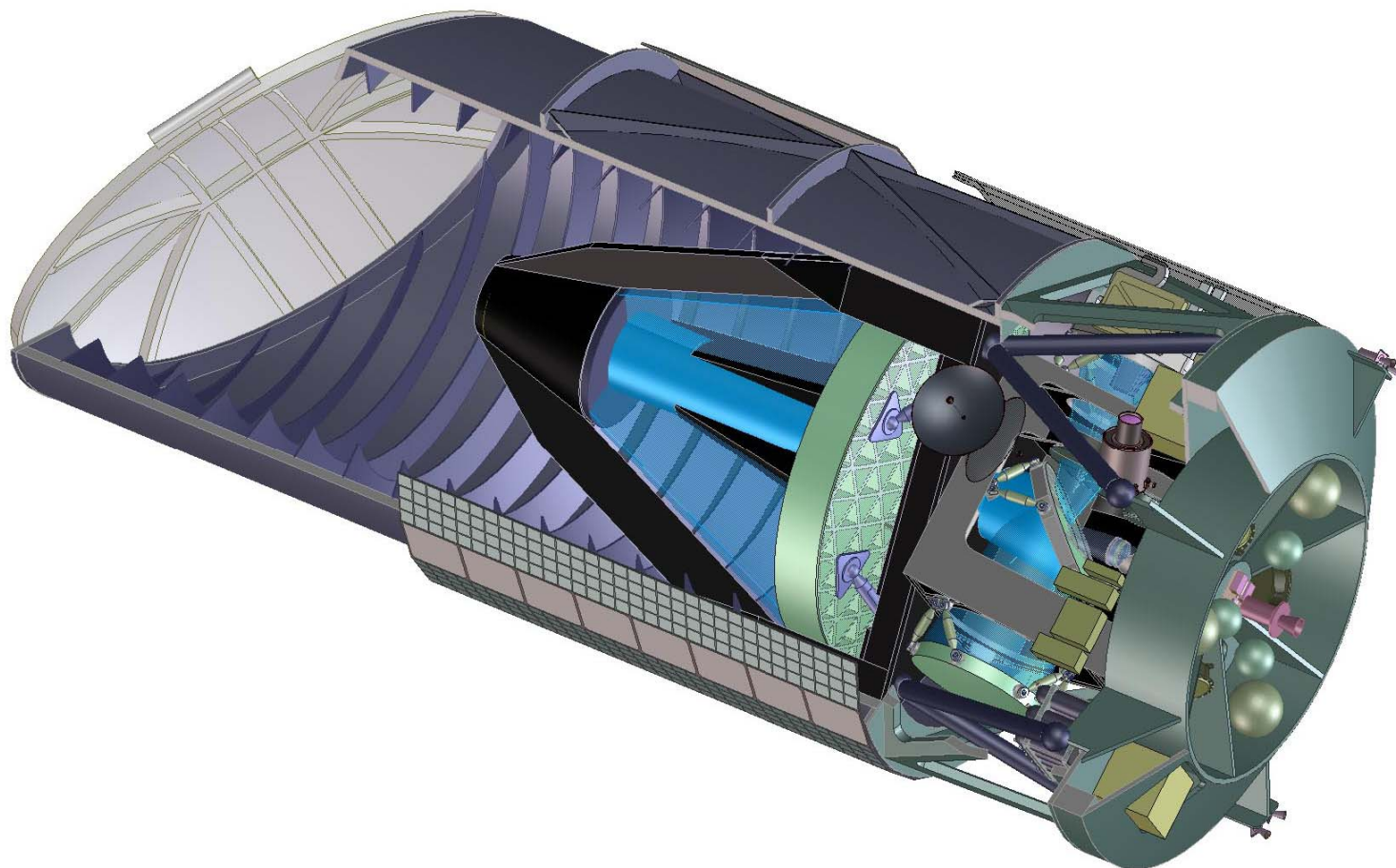
Quantum gravity, supergravity, extra dimensions?

We need new, highly precise data.

We need intensive theory and phenomenology to design experiments and interpret data.

SNAP: The Next Generation

Dedicated dark energy probe



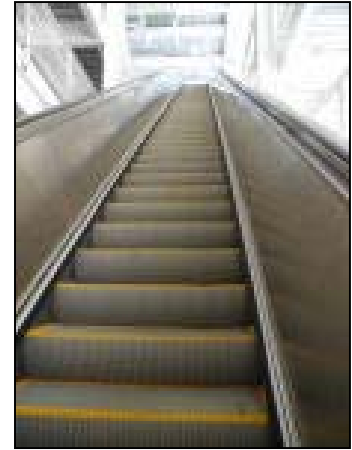
Nearby
Supernova
Factory

Aldering

SNAP: Supernova/Acceleration Probe

Weak Gravitational Lensing

Dark energy accelerates the expansion.
This stretching of distances (*SN Ia probe*)
shuts down the growth of structure (galaxies,
clusters of galaxies).



Gravity bends light...

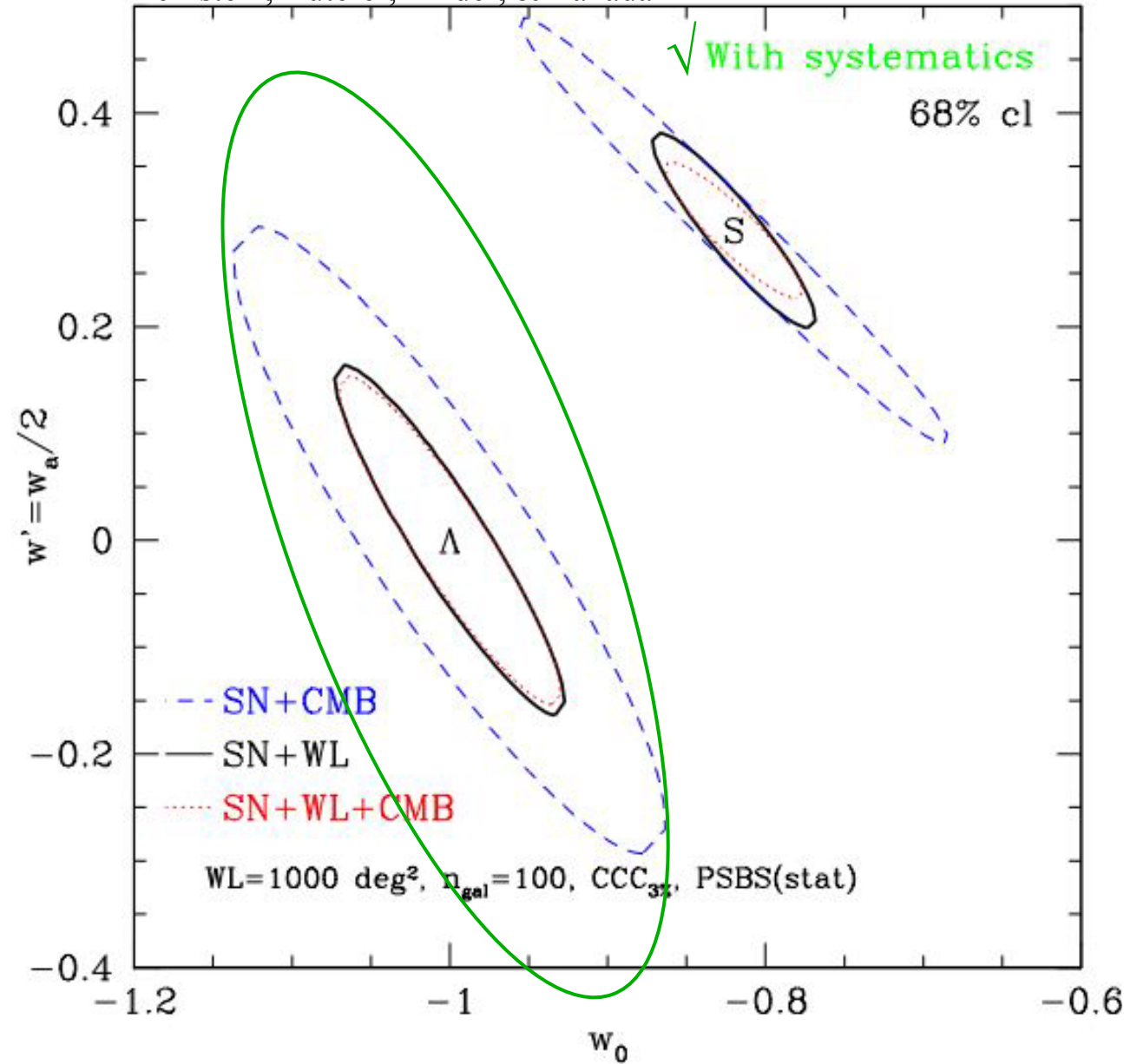


- objects are magnified and distorted (*shear*)
- so we can detect *all* matter (even dark matter) through its gravity
- by observing the distortions as a function of redshift, we can view “CAT scans” of growth of structure

So by measuring the growth history, lensing can detect the level of acceleration: the amount of **dark energy** and its equation of state ratio $w(z)$.

Supernovae + Weak Lensing

Bernstein, Huterer, Linder, & Takada



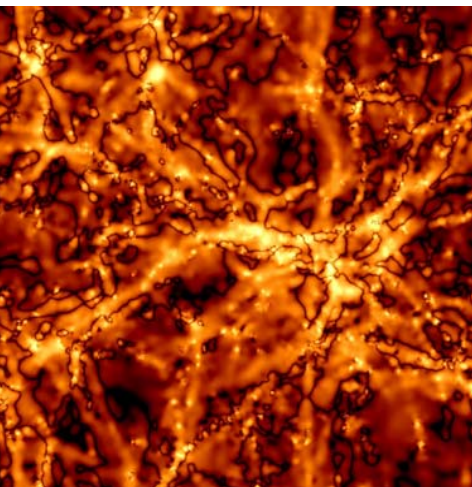
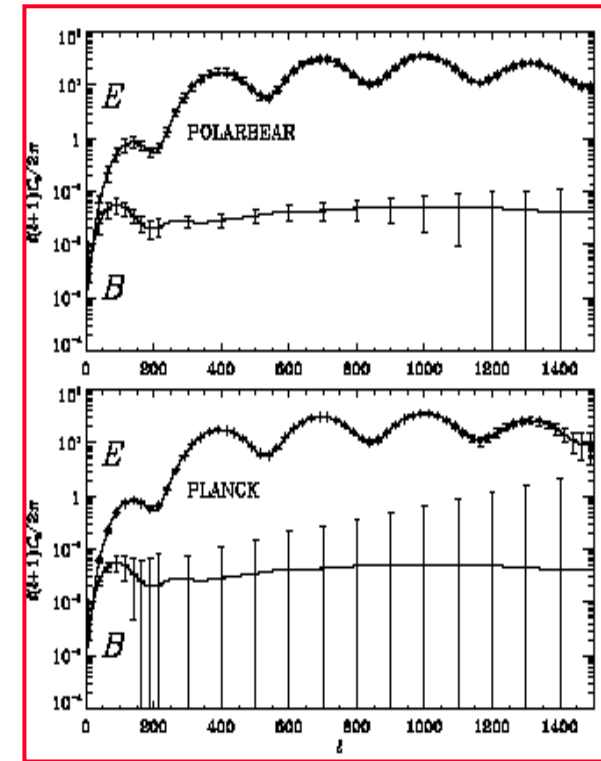
- **Comprehensive:**
no external priors required!
- **Independent test of flatness to 1-2%**
- **Complementary:**
 w_0 to 5%, w' to 0.11
(*with systematics*)
- **Flexible:** if systematics allow, can cover 10000 deg²

Dark energy *may* not be just Λ
Inflation *is not* just exponential expansion

Physics (energy scale, exit) in
Inflationary Gravitational Waves

Measurable by polarization

Experiment: **PolarBear** (2006)



SZ Effect – an undimming flashlight

Map out nonlinear structure, clusters

Experiments: **APEX** (2005), **South Pole Telescope** (2007)

In observations, we are systematics limited.
In interpretation and design, we are *theory* limited.

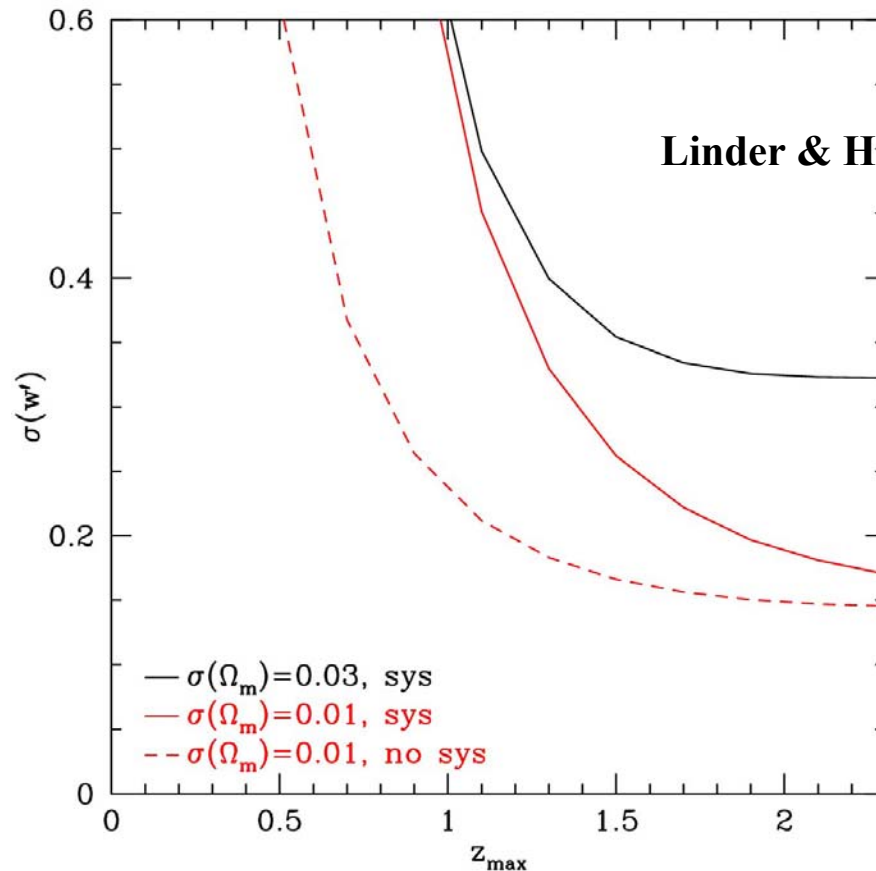
We need to understand

- Fundamental ties between cosmology, quantum, gravity
- Expansion of the universe vs. equation of state
- Interactions between theory and experiment design/analysis
- Nonlinear gravity and growth of structure (lensing, galaxy clusters, CMB)

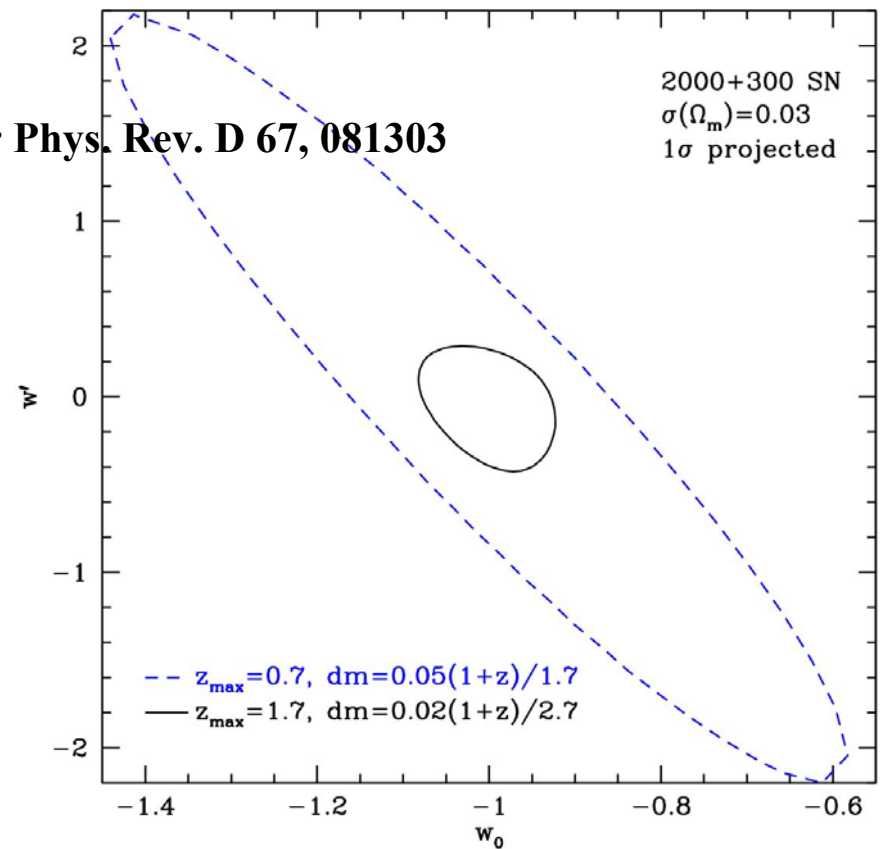
Intensive cosmology theory work is needed to design the experiments and interpret data.

Essential Theory: Supernova Redshift Range

Question of redshift range, ground vs. space laid to rest at Lehman Review 2002 by theory work --
“convincingly established”.



Linder & Huterer Phys. Rev. D 67, 081303



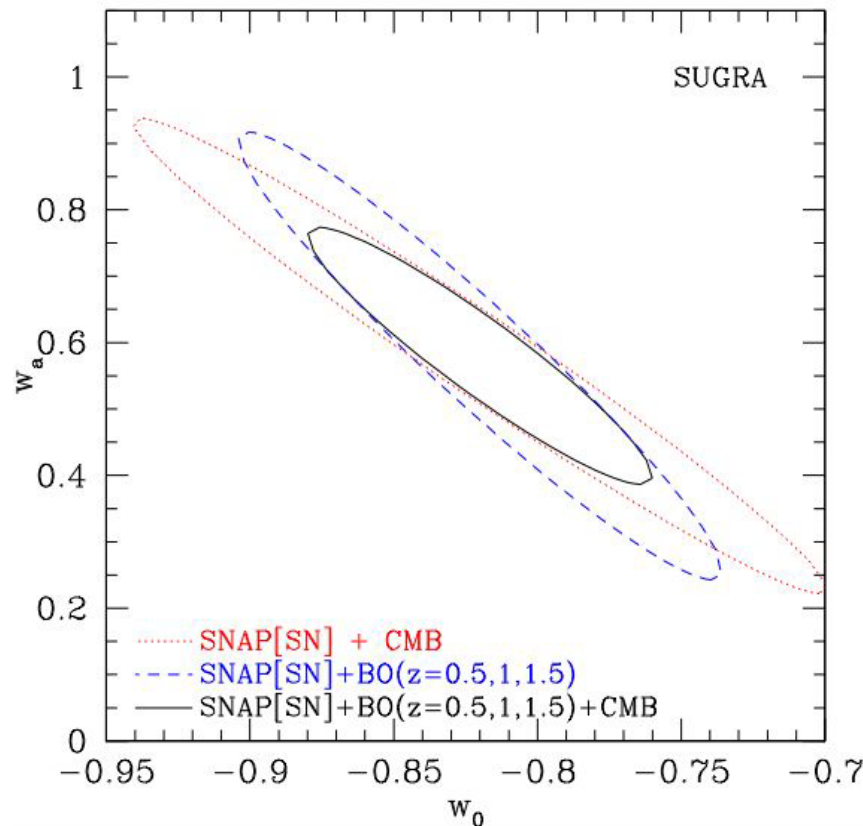
$z \approx 1.7$ is optimal

Deep SN surveys represent a major advance in understanding dark energy

Essential Theory: Designing Experiments



Baryon acoustic oscillations (3D galaxy distribution)
- probes primordial fluctuations in matter, cousin to those in CMB radiation



Baryon oscillations have excellent complementarity with supernovae probes

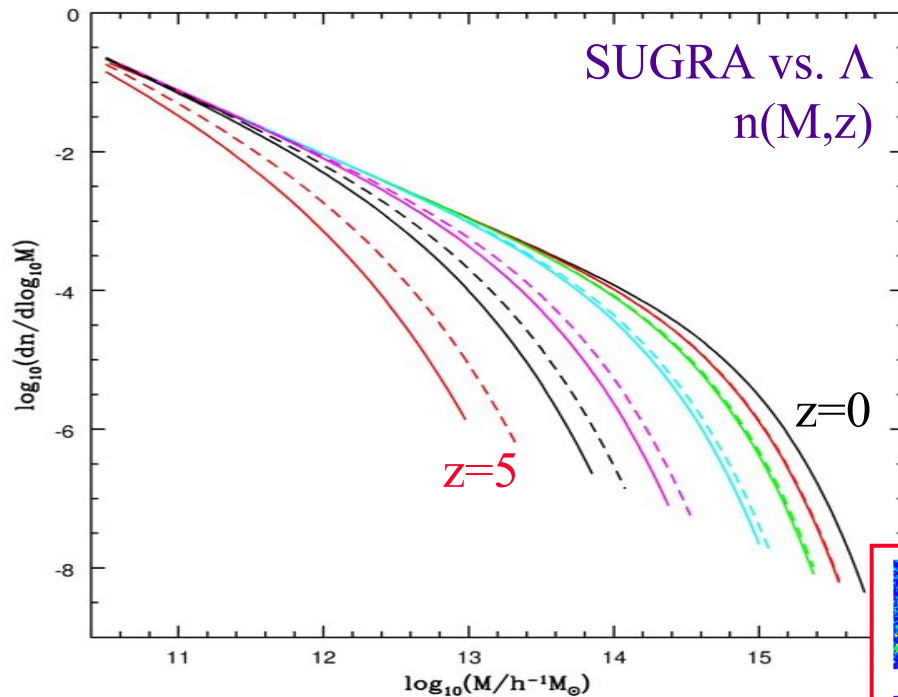
Linder 2003, Phys. Rev. D 68, 083504

Essential Theory: Simulating Experiments



Mapping gravity, mapping mass

- nonlinear regime requires dedicated simulations

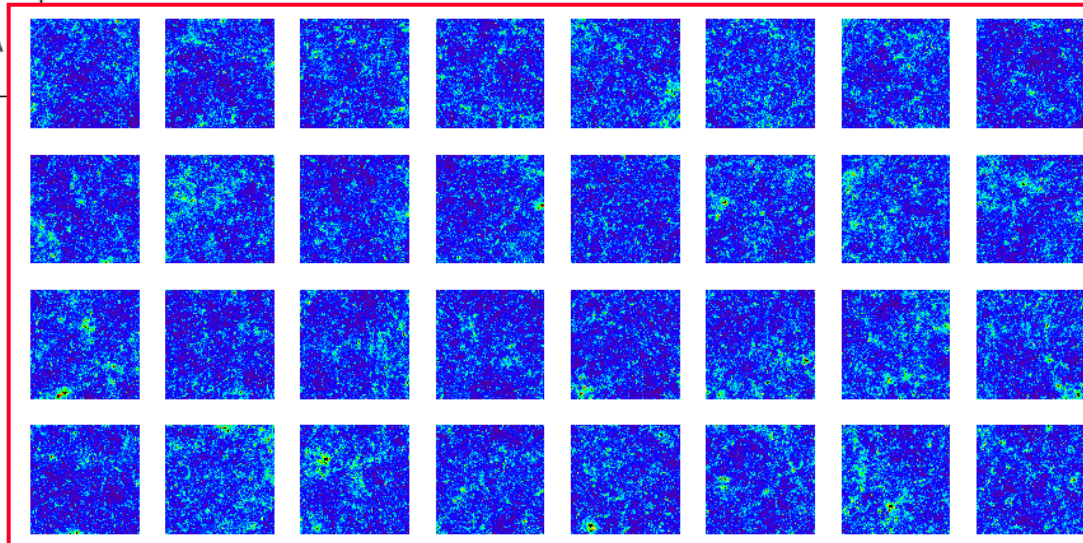


First dynamical dark energy simulation

Linder & Jenkins 2003, MN Royal
Astronomical Soc. 346, 573

Maps of weak gravitational lensing (dark structure)

White & Vale 2004, Astropart. Phys. 22, 19

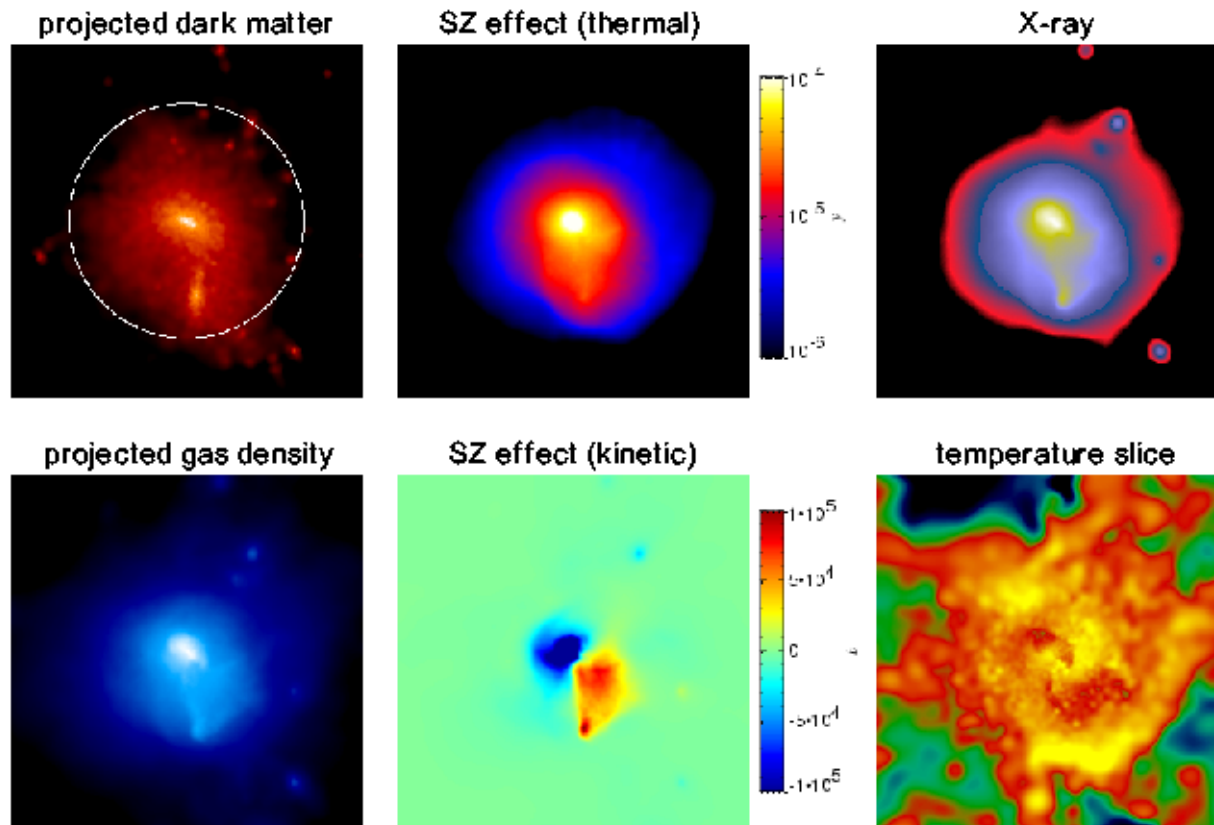


Essential Theory: Interpreting Experiments

White 2003, Astrophys. J. 597, 650

Combined measurements of X-ray, and thermal & kinetic SZ
are powerful tools to study the structure of clusters

A CLUSTER SEEN IN DIFFERENT WAYS



To develop state of the art experiments, one
requires state of the art theory.

A grand challenge: all the work of the Standard+ Model covers 30% of the universe.

Before us lies the unknown 70%!

What is dark energy?

Will the universe expansion accelerate forever?

Does the vacuum decay? Phase transitions?

How many dimensions are there?

How are quantum physics and gravity unified?

What is the fate of the universe?

Meeting the Challenge

